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A SURVEY OF RESEARCH PROBLEMS IN GEOPHYSICS

PREPARED BY CHAIRMEN OF SECTIONS OF THE AMERICAN GEOPHYSICAL UNION

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These papers were presented at the first annual meeting of the American Geophysical Union, by the chairmen of the several sections of the Union. The meeting was held at the National Research Council in Washington, D. C., on April 23, 1920. The American Geophysical Union is also the Committee on Geophysics of the National Research Council and is the National Committee for the United States of the International Geodetic and Geophysical Union.

PRESENT STATUS OF GEODESY AND SOME OF THE PROBLEMS OF THIS BRANCH OF GEOPHYSICS

BY WILLIAM BOWIE

Geodesy is one of the oldest of the geophysical sciences. Originally it embraced only a limited field, consisting of the determination of the shape of the earth and its size and the means by which this was done. But now the subject of geodesy is very closely allied with other matters and there are few geophysical questions that do not, either directly or indirectly, concern the geodesist in the solution of his problems.

Almost every country of the world that pretends to any standing has organized a service for the purpose of carrying on what are called geodetic surveys. As a matter of fact, any survey of the land in which the shape and size of the earth are taken into consideration can be called geodetic; thus, the hydrographic surveys along the coast made for a sailing chart are really geodetic surveys and, similarly, a topographic survey of a large area may be considered to be a geodetic survey; but what I have in mind in speaking of geodetic surveys, are triangulation, base measurements, precise leveling, etc.

By means of base measurements and triangulation, the geographic positions of places are determined which are of immense value in the permanent establishment of boundary lines between nations and political sub-divisions of a nation, for the control of various classes of surveys and maps, and for other engineering purposes.

Practically the whole of Europe has been covered by a system of points whose latitudes and longitudes have been determined by triangulation. This is also the case in Japan and in India. Australia, portions of Africa, and some of the countries of Central and South America have made good starts towards extending triangulation over their areas. In the United States excellent progress has been made in this work. There is triangulation around the entire border and there are many arcs in the interior of the country from which triangulation of precise or lower grades may be extended into every area in which detailed surveying and mapping operations are to be carried on.

It will be of interest to outline briefly the methods for carrying on triangulation or trigonometric surveys.

In the first place a spheroid of reference must be adopted which will approximate the actual shape and size of the earth. Then there must be an initial point whose astronomic latitude and longitude have been observed. Next is needed the azimuth or true bearing of a line of which the station occupied forms one end. After these data are available it is necessary to measure with extreme accuracy the distance between two intervisible points on the earth's surface to serve as a base. After the length of the base is known, additional stations are selected with a view to forming triangles by lines which are clear of obstructions and thus intervisible between their ends. It is, of course, a well known mathematical principle that when a side and the angles of a triangle are known, the other sides can be computed. When these sides have been computed from the base, either one of them can be used as the base for a new triangle. In a similar manner we may extend the computations through a long chain of triangles extending in some cases hundreds of miles across a country.

When the base has been measured and the angles observed and the computations of the triangles have given the lengths of the sides of the triangles, then computations can be made which will give the latitude and longitude of each point and the bearing of each line based on the data for the initial point, at which the astronomic latitude and longitude were observed and the true bearing determined of one line of the triangulation.

This is the simplest case of a geodetic survey where the whole net work depends on some initial astronomic station.

In practice, we have a much more complicated situation. Geodetic surveys have been started from many widely separated astronomic stations and the triangulation based on each has been finally extended until it meets the triangulation nets based on other astronomic stations. When this has been done, it is always found that the geographic positions computed from one astronomic station will differ from the geographic positions of the same points computed from other astronomic stations. We have a very striking example of this on the island of Porto Rico. The astronomic latitude was determined at Ponce, on the southern coast, and at San Juan on the northern coast of the island. The distance across the island, in a north and south direction, between these stations, is approximately thirty miles. The distance between the two stations, as computed from their observed astronomic positions, differs by about one mile from the distance between the two as determined by triangulation. The triangulation distance is correct within ten feet. The cause of this difference in distance as determined by the two methods is the attraction of the mountain mass, forming the Island of Porto Rico, on the plumb line to which the astronomic observations are referred. To the northward of Porto Rico are the deepest parts of the Atlantic Ocean and just to the southward of the island is a vast depth in the Caribbean sea. It can be readily seen that the effect of this distribution of mass in the oceans and in the island and its base is to draw the plumb line towards the centre of the island. This would throw the zenith on the south shore too far to the south and the zenith at the north shore station too far north. The plumb lines projected against the celestial sphere would therefore include a greater arc than they would under normal conditions. This angle is actually about 56 seconds of arc greater than normal.

In carrying on a geodetic survey, as described above, it is necessary to know accurately the elevations of the base lines and triangulation stations above the so-called plane of reference which is mean sea level. Each line that is determined by the triangulation is referred to sea level, that is, the computed distance between any two stations is the distance, along the geoid or sea level surface, between the points where the plumb lines at the two stations pierce this surface. Accurate elevations are also needed in many phases of surveying, in mapping, and in other engineering operations. They are also essential in many branches of science, notably in meteorology, geology, etc.

In order that elevations may have the maximum value to engineers it is necessary that they all be referred to the same, so-called, plane of reference. The one which has been almost universally adopted is mean sea level. It may be defined as the surface which would coincide with the surface of the oceans and their tide water branches if the tide producing forces should cease to act and there were no movements of the air and the barometric pressure were uniform. This surface can be determined at any point on the exposed coast by continuous tidal observations for approximately three years. The mean of the hourly readings of the tide record for such a period is practically free from error. If observations were made for a long period of years, it would be found that the average position of the surface of the ocean, for one three-year period, would agree very closely with the position of the surface for any other three-year period. The difference, if any, would be very minute.

It has been assumed by geodesists that, insofar as engineering work is concerned, mean sea level at each place along an open coast is in the same equipotential surface. This, of course, cannot be absolutely true because of different densities in the waters of the oceans, different barometric pressures, trade winds, and possibly other causes, but the deviation of mean sea level at one station from the equipotential surface containing mean sea level as determined at another station is so small as to be negligible in surveying, mapping, and other engineering work, and for practically all scientific purposes.

After the mean sea level surface has been determined, lines of very accurate spirit leveling are extended inland from the fundamental tidal stations. Each country of the world has done more or less of this work and in the United States we have tens of thousands of miles of this grade of leveling.

When a network of triangulation has been extended over a large area and astronomical latitudes, longitudes and azimuths have been observed at many of the stations, differences between the astronomic and geodetic positions of the stations are found. These differences are due to the deflection of the vertical, as was explained in the case of Porto Rico, and to the fact that the spheroid of reference used in computing the geographic positions of the triangulation stations differs from the actual figure of the earth. The former differences, namely, those due to deflections of the vertical, tend to be more or less accidental in character, while those due to an erroneous spheroid of reference are systematic.

After the triangulation and astronomic work have been done over an extensive area, the shape and size of the mean figure of the earth may be computed with a higher degree of accuracy, possibly, than the spheroid of reference on which the triangulation was originally based. For one hundred years or more we have made closer and closer approximations to the true figure of the earth, as the triangulations of the various nations have been extended. In the earlier of these determinations there was considerable uncertainty, owing to the deflection of the vertical caused by mountain masses and other topographic features. Some of the determinations of the figure of the earth were based on all of the observed geodetic data, that is, triangulation and connected astronomic stations, and other determinations were made to depend only on those data from which stations with large deflections of the vertical had been eliminated.

In the late fifties of the past century, Archdeacon John H. Pratt announced the theory that the geodetic data seemed to indicate that under mountain masses there were deficiencies of matter approximately equal in quantity to the masses that were above sea level. This theory was frequently commented on and studies were made to intepret certain geological features by means of it.

In 1889, Major C. E. Dutton, in an address before the Philosophical Society of Washington, entitled "On some of the greater problems of physical geology,"[1] applied the term "isostasy" to this theory of equal pressure, that the mountains are accompanied by deficiencies of mass under them and that there is an excess of matter under the oceans.

About fifteen years after Dutton gave prominence to this theory, Prof. John F. Hayford, at that time Chief of the Division of Geodesy of the United States Coast and Geodetic Survey, began investigations which showed rather conclusively that the material above sea level is counterbalanced to a marked degree by a deficiency in density of material in the column directly under the exposed material. This column, which is affected by this decreased density, was found by Hayford to extend to a depth of approximately 122 kilometers, if the compensation is assumed to be uniformly distributed. Hayford also found that the column extending approximately 122 kilometers below the bottom of the ocean has a density in excess of normal that will balance approximately the deficiency of matter in the mass of water directly above the column.

This condition of approximate equilibrium in the earth's material at a depth of approximately 122 kilometers was applied by Hayford in determining the figure of the earth from geodetic data in the United States. The results appear in his report published in 1909,[2] which gives dimensions for the earth that are believed to be of a higher order of accuracy than any previously arrived at. This is because the theory of isostasy was considered in this work. It is hoped that in the future the theory of isostasy can be considered in deriving a figure of the earth from all available triangulation data in the world.

In order that this figure of the earth may be computed it will be necessary to have some central office to guide the investigators of the several countries who may assist in the work. Undoubtedly this central office should be under the direction of the Division of Geodesy of the International Geodetic and Geophysical Union, although the central office itself might be located in a geodetic organization of any one of the countries adhering to the union.

In North America great progress has been made in coördinating the geodetic work of the several countries. Some years ago, there was adopted for the triangulation net of the United States what was called the United States Standard Datum. This datum had its designation changed to North American Datum when, in 1913, it was adopted by Canada and Mexico. It is hoped that within a few years a continuous triangulation will be extended into Alaska from the United States and then that territory can also have its triangulation placed on the same datum as the rest of the continent.

A datum may be defined as the adopted latitude and longitude of some station of the triangulation and the azimuth of a line of the triangulation radiating from that station. It also includes the dimensions of the reference spheroid, on which the triangulation is computed.

The advantages of a single datum are, first, that it makes it possible to compute the figure of the earth with greater accuracy and, second, that it avoids the confusion existing in the maps at the frontier of any country when the adjoining countries base their surveys and maps on different datums. Whenever the datums are different, boundary monuments have different geographic positions on the maps of the two countries and there are overlaps, gaps, and offsets in the maps, which frequently result in controversies over the boundary line.

One of the greatest needs in Europe to-day, from a geodetic standpoint, is the adoption of one datum for the whole of its area. This would involve a tremendous amount of revision of the computation and adjustment of the triangulation nets of the several countries, but the resulting benefits would far offset the cost of the work.

Trigonometric leveling is a branch of geodetic work which, though important, is not as much so as triangulation and precise leveling. It is employed in determining the elevations of the triangulation stations in order that the lines observed may be corrected to what they would be if the observations were made at sea level. Theoretically, trigonometric leveling should furnish data from which to compute the shape of the geoid, but this is impracticable owing to our inability to know the exact value of the atmospheric refraction at the instant of observation. Trigonometric leveling is of value in determining the elevations of mountain peaks used as stations or those outside of the main scheme of the triangulation. It is by this method that the elevations of Pikes Peak, Mt. Everest, Mt. McKinley and many others, have been determined.

A branch of geodetic work which has been receiving great attention during the past decade or more is the determination of the intensity of gravity. For a number of years observations were made using reversible pendulums in order to determine the absolute value of gravity. Following this, observations were made with what were called invariable pendulums approximately one meter in length, to get the relative value of gravity or the difference in gravity between two places, one of which was the base station. These results were not particularly satisfactory because the pendulums were swung in the air with rather poor temperature control and the effect of the flexure of the support due to the swinging pendulum was not considered, or, if it was, was not accurately determined.

About 1885, Von Sterneck devised an apparatus which consisted of a quarter-meter pendulum of the invariable type, swung in a case from which the air could be almost entirely exhausted. With this apparatus, the difference in gravity between two stations could be determined with a high degree of precision. There have been modifications of the Von Sterneck pendulums, but only in minor features, the general principle of the apparatus remaining unchanged until this time.

With the short pendulums of the Von Sterneck type it was possible to establish a station in a very short time and at a very low cost. The result has been a great stimulation of effort in this branch of geodetic work. Most of the countries of the world carrying on geodetic operations have adopted this type of pendulum and many stations have been established.

In 1908 there were 47 modern gravity stations in the United States, while to-day there are 276 such stations.

Gravity determinations have a number of uses; one is to furnish a formula by which the value of gravity can be computed for any latitude for use in the physical and chemical sciences; another, to furnish data by which the shape of the earth may be determined; and another, to furnish data for making studies of the theory of isostasy or the deviation from normal densities of matter in the outer portion of the earth.

As a result of the application of the theory of isostasy to the gravity determinations in the United States, the shape of the earth, or rather the amount of its flattening, has been determined by investigations made by the Coast and Geodetic Survey and published in 1917 as Special Publication No. 40 of that Bureau. The reciprocal of the flattening was found to be 297.4. This value is probably the most reliable one in existence to-day. There were also derived from this investigation new constants for the gravity formula for computing the value of gravity at any latitude. This formula was adopted by the U. S. Weather Bureau and by the Smithsonian Institution in the preparation of the latest edition of the Meteorological Tables. In that investigation was also determined the depth of compensation; that is the depth at and below which the materials of the earth are supposed to be in a state of equilibrium. This depth was found to be 96 kilometers, which agrees very closely with the value derived by Hayford in his determination of the figure of the earth at stations in mountainous regions only. It is necessarily true that a depth of compensation can be derived from data in elevated regions with greater certainty than where the land is low. The higher land is liable to be freer from constant or systematic deviation from normal conditions in the immediate vicinity of a station.

The gravity observations not only give a means of determining whether there are regional deviations from normal densities in the outer portion of the earth under the continents and oceans to cause equilibrium at the depth of compensation, approximately 96 kilometers, but they also afford an opportunity to detect abnormal densities in the materials of the earth which are close to the surface but below sea level. Recent investigations in the United States and in India show a decided relation between the value of gravity and the Cenozoic geologic formation. This formation is approximately 10% lighter than the material in the older geological formations. Pendulum observations may be a means of indicating the approximate depth to which the Cenozoic formation extends at any place.

Gravity observations also indicate a relation between the value of gravity and the Pre-Cambrian formation. In this formation the material is, in general, somewhat heavier than normal, and when a gravity station is established at or near Pre-Cambrian rocks the value of gravity is found in most cases to be greater than normal. It is not improbable that a knowledge of this relation between the Pre-Cambrain formation and the gravity anomaly may make it possible to discover crystalline rocks or others that are extra heavy which may be covered by materials of normal or lighter densities. If this proves to be the case, it may be possible to locate areas underlaid by dense rocks close to the surface of the ground, which may have an economic importance in connection with boring for oil. Much money has been lost by oil prospectors in drilling in regions which have been found by them to be underlaid by crystalline rocks.

It is seen that gravity determinations have much more than a purely geodetic value. The results obtained from them will undoubtedly have a very great effect on the science of geology.

There are geophysical problems that would be considerably cleared up if the value of the intensity of gravity over the oceans could be determined accurately. Such observations would make it possible to determine whether the outer portion of the earth under the ocean is in the same isostatic condition as has been found under the continents. It would seem probable that isostasy obtains to the same extent under the oceans as under the land, but it has not been possible to prove this in the absence of accurate gravimetric determinations on the ocean.

It is true that gravity observations have been made over the ocean, but the apparatus, in each case, lacked the necessary precision to give the value of gravity with a sufficiently high degree of accuracy. It is probable that improvements will be made in the apparatus for determining gravity at sea and when one has been perfected to such an extent that it will give results of adequate accuracy, a long step forward will have been made in geodesy.

The theory of isostasy has some corroborative evidence in the form of a relation between the elevation of the ground and the density of the igneous rocks. Recently Dr. H. S. Washington delivered a paper at a meeting of the Geological Society of Washington in which he showed very conclusively that the higher the elevation at which igneous rocks are found, the smaller the density of such rocks. This tends to confirm the theory of isostasy which postulates the higher the land the less the density in the column under it, down to some indefinite depth called the depth of compensation, approximately 96 kilometers.

It is hoped that these studies by Dr. Washington may be continued by him and by others, for their results will undoubtedly be of great value to geophysicists in general and especially to geologists working in the subject of isostasy.

Another matter that is assuming importance in geodesy is the determination of earth tides. These were studied by the International Geodetic Association, a station having been established for this purpose in Europe some years ago. The apparatus used was of sufficient delicacy to show that there is an earth tide caused by the tide producing forces of the moon and sun, but it could not be considered that the results obtained were entirely satisfactory. This condition has been changed, as a result of the construction of an earth tide apparatus by Prof. A. A. Michelson, of the University of Chicago. This apparatus consists essentially of two tubes placed horizontally in the ground, one in a north and south and the other in an east and west direction. These tubes are partially filled with liquid and the tide producing forces cause an inclination of the liquid surfaces, producing the phenomena of tides. The actual amount of tilting of the surface of the liquid is determined by the interferometer method.

The differences between the tides, as observed in the horizontal tubes, and the theoretical tides that would be produced on the earth, if it were rigid, give the measure of the actual distortion of the earth itself. This apparatus of Prof. Michelson is considered to be entirely satisfactory and it is hoped that it may be used nationally and internationally in determining the value of the earth tides at different parts of the earth and under different geological conditions.

From the result of the earth tides, values can be deduced for some of the physical properties of the material of the earth, such as elasticity and viscosity, at different distances from the surface. A knowledge of these will be of great geophysical value.

Seismology is a geodetic subject in the sense that it throws light on the constitution of the interior of the earth and thus assists in investigations of the shape of the earth. As was said in the first part of this paper, geodesy originally had as its function the determination of the figure of the earth, but in order to ascertain why the figure of the earth is such as we find it, a knowledge of the physical characteristics of the material composing the earth is essential. Seismology in connection with the investigation of the earth tides should furnish much information regarding the physical properties of the material of the earth at various depths.

A subject that is of interest to many geophysicists as well as to astronomers is the variation of latitude which has been studied for a number of years by the International Geodetic Association. While certain parts of the variation have been found to follow certain laws of change there are still apparent irregularities not yet explained.

From investigations dating back to Euler's time it was at first supposed that the latitude variation, if found, would have a period of about ten months, this being on the supposition of a rigid earth. It is found that the principal part of the polar motion has a period of 14 months. From this fact it is inferred that the earth is not rigid, and from the numerical amount of the lengthening of the period we may draw inferences as to the elastic properties of the earth as a whole; these inferences agree in a general way with what has been found by investigations along other lines. We naturally expect the shifting of the pole to be accompanied by a shifting of the ocean waters responding to the change in the centrifugal force of rotation. This latitude-variation tide has already been studied to some extent without in any way exhausting the subject.

This problem of determining the variation of latitude at observatories is really an astronomic one, although it has a geodetic bearing. The figure of the earth, determined from triangulation and astronomic data, is affected though very slightly by this variation. When it was found desirable to carry on systematic observations on an international scale, there was no astronomic organization with sufficient funds to do the work. The problem was presented to the International Geodetic Association, which had a source of funds not available to the International Astronomic Society. The result was that the International Geodetic Association undertook the work and has carried it on continuously, even during the war, for twenty years or more. The work must not be discontinued nor should there be any break in the observations at the international stations in Italy, Japan and the United States.

Geodesists are interested in the science of volcanology or at least in certain phases of the work in that science which may throw light on the constitution of the material, with densities and temperatures, in the outer portion of the earth, and the cause of volcanic activity. It is believed that these data will supplement the information obtained from the several other lines of investigation such as gravity determinations, earth tides, seismology and variation of latitude.

There is another subject which is of particular importance to geophysicists and, I might say, of very great interest to geodesists. This is what may be called geo-mechanics. It would embrace an investigation to show the relation of forces to movements of material, the origin of forces, and their causes. It would really combine the subjects of isostasy, earth tides, variation of latitude, seismology, and certain phases of volcanology. The data collected in those branches of geophysics should be considered in connection with geology in order to interpret in the light of present knowledge the various movements that have taken place in the earth. Up to this time, it is believed that these data have not been given due consideration and weight in the study of the earth, its structure, forces, etc.

Some of the subjects that have been discussed above are only incidentally related to geodesy, but the results of investigations in them are certainly of great value and interest to geodesists and it is believed that there should be committees of the Section of Geodesy of the American Geophysical Union to consider these questions and be able to inform the members of the Section at any time as to the progress made in these branches of geophysics. There are several of the subjects which have sections of their own, for instance, those of Seismology and of Volcanology.

The Geodetic Section of the American Geophysical Union will not attempt, nor does it desire, to pre-empt any field of geophysics nor will it encroach on the rights and privileges of any other organization. It will simply attempt to keep informed of what is going on in the various fields of geophysics which are of interest to geodesists and it hopes that it may from time to time give some assistance to other organizations in suggesting problems or lines of research. On the other hand, it stands ready to receive suggestions and help from any other organization dealing in any branch of geophysics.

[1] *Bulletin of the Phila. Soc. of Washington,* **11** (51–64).

[2] Supplemental Investigations of the Figure of the Earth and Isostasy from Measurements in the United States.

THE PROBLEMS OF SEISMOLOGY

BY HARRY FIELDING REID

Although earthquakes have received sporadic attention for some time in the past, their systematic study may almost be said to have begun with Mallet about the middle of the last century; and it was only towards the end of the century that instruments delicate enough to register distinct shocks were developed, making it possible to gain some knowledge of the characteristics of earthquake vibrations and the velocities with which they are propagated through the earth. But, notwithstanding the shortness of the time during which these studies have been in progress, the science has been well outlined and first approximations to the solutions of many of its problems have been obtained. The time has now arrived